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14. ABSTRACT
Recent research at the Air Force Research Laboratory (AFRL) has addressed the difficult problem of lightweight, blast-resistant doors which can be used in structural retrofits (or new construction) to combat the threat of terrorist bombing. Doors have always been one of the weakest points in most structures, primarily because of the requirement for convenient human access. In some hardened structures, very thick steel doors provide adequate blast protection; but these heavyweight doors are not readily adaptable to more general-purpose, lighter-weight structures, such as businesses and homes. The design problems which must be addressed in creating a lightweight, blast-resistant door can be grouped into three general areas: (1) the door must be lightweight; (2) the door must be capable of withstanding the blast-pressure; and (3) the frame must be capable of holding the blast-resistant door. The first two areas are obvious, but the latter is often overlooked. Stated more specifically, if the "blast-proof" door cannot be contained by the door frame, it will become a large, rigid, and life-threatening projectile. The body of the paper focuses on the specific materials and techniques used to create the AFRL lightweight, blast-resistant doors. These doors use a patent-pending design to resist blast-pressures far above any commercially-available "lightweight" door. In fact, the AFRL blast-resistant doors can achieve protection, with a relatively simple retrofit, that would otherwise require significant and substantial structural modifications. Results from AFRL blast tests on the doors are presented, which clearly show their capability under extremely high blast pressures. Finally, a discussion of the design concepts used in the AFRL lightweight, blast-resistant doors is presented which shows that the door design is scalable, i.e., that doors of other widths and heights can be produced using the same basic design process.

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Doors, Membrane Action, Damping Chamber, Blast-Resistant, Protective Design, Retrofit

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LIGHTWEIGHT, BLAST-RESISTANT DOORS FOR RETROFIT PROTECTION AGAINST THE TERRORIST THREAT

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ABSTRACT

Recent research at the Air Force Research Laboratory (AFRL) has solved the difficult problem of lightweight, blast-resistant doors which can be used in structural retrofits (or new construction) to combat the threat of terrorist bombing. The overriding key in all "protective designs" is to define the weakest points in a structure and then reduce the threat at those points. Doors have always been one of the weakest points in most structures, primarily because of the requirement for convenient human access. In some hardened structures, very thick steel doors provide adequate blast protection; but these heavyweight doors are not readily adaptable to more general-purpose, lighter-weight structures, such as businesses and homes. The design problems which must be addressed in creating a lightweight, blast-resistant door can be grouped into three general areas: (1) the door must be lightweight; (2) the door must be capable of withstanding the blast-pressure; and (3) the frame must be capable of holding the blast-resistant door. The first two areas are obvious, but the latter is often overlooked. Stated more specifically, if the "blast-proof" door cannot be contained by the door frame, it will become a large, rigid, and life-threatening projectile. The paper first briefly discusses the evolution of the extraordinary AFRL door design. For example, basic design concepts gleaned from previous AFRL work on blast protection are briefly discussed in the context of their adaptation into the door design. However, the body of the paper focuses on the specific materials and techniques used to create the AFRL lightweight, blast-resistant doors. These doors use a patent-pending design to resist blast-pressures far above any commercially-available "lightweight" door. In fact, the AFRL blast-resistant doors can achieve protection, with a relatively simple retrofit, that would otherwise require significant and substantial structural modifications (modifications which may not even be possible in many lighter-weight structures). Results from AFRL blast tests on the doors are presented, which clearly show their capability under extremely high blast pressures. Finally, a discussion of the design concepts used in the AFRL lightweight, blast-resistant doors is presented which shows that the door design is scalable, i.e., that doors of other widths and heights can be produced using the same basic design process.

Keywords: Blast resistant, doors, retrofit, blast pressure.

BACKGROUND *(Dover, Anderson, and Vickers 2002)*

In the 1990s, concerns about a "combined threat" became a significant issue for the Air Force, particularly with respect to points of entry (i.e., windows and doors). The "combined threat" is the use of an explosive pressure wave to expose the inside of a structure to chemical or biological attack. In the past, research on blast-resistance for points of entry had concentrated on eliminating such problems as shrapnel (i.e., explosive fragmentations), direct concussion, and indirect concussion effects (e.g., flying books or overturned furniture).

Until recently, military studies on blast-resistance were based on a set of threat conditions generally referred to as the "Warsaw threat." However, with the recent fall of the Berlin Wall and the breakup of the Soviet Union, there was a de-emphasis on research to support NATO-type structures. More recently, however, there has been renewed interest in the combined threat. For example, the use of aircraft as bombs by *al-Qaida*, followed soon after by the use of Anthrax by unknown terrorists (not to mention the possibility that West Nile virus was intentionally introduced) has implicitly increased the awareness of the combined threat in the civilian population of America. In addition, the international community, and Israel in particular, was made aware of the combined threat by the actions of Iraq in the Gulf War era. That is, during the Gulf War, Iraq used SCUD missiles in attacks on civilian targets (mainly in Israel); and soon after the Gulf War, Iraq used chemical weapons on its own dissidents. This willingness of a single country, or terrorist groups (known or unknown), to use both explosive and chem-bio agents has greatly increased the interest in developing retrofit techniques for resistance to the combined threat.

Windows have traditionally been viewed as the weakest structural component with respect to blast protection; but for the combined threat, the doorway offers a special design challenge because of the conflicting needs of sealing for protection and providing easy entry. To solve the combined threat problem for windows, the Air Force Research Laboratory (AFRL) designed a set of patent-pending blast-resistant windows formally known as "Blast Proof Window Systems with Damping Chamber,[PP]" and informally known as the "Flex" window (*Anderson and Dover 2003*). The Flex window was designed specifically to combat the combined threat from terrorist organizations, rogue nations, and / or person or persons unknown, and was designed to be useful in both new and retrofit construction scenarios. With a solution for the window problem in hand, AFRL turned its attention to the problem of a lightweight, blast-resistant door.

Traditionally, blast-resistant doors were used in hardened structures, and relied on high strength and mass to provide blast-resistance. However, these massive doors are not readily adaptable to more general-purpose, lighter-weight structures, such as businesses and homes. To be most useful, particularly for retrofit, the door must: (1) be lightweight; (2) be capable of withstanding the blast-pressure; and (3) must have a frame capable of supporting the door under blast loading. If the door is not lightweight, it will not allow easy entry. Obviously, the door must resist the blast pressure. Less obviously, if the "blast-proof" door cannot be contained by the door frame, it will become a large, rigid, and life-threatening projectile. All three design needs are met by the patent-pending AFRL Accordion-Flex[PP] door.

INTRODUCTION

Figure 1a shows a labeled schematic of the Accordion-Flex door. This door design draws heavily on lessons learned from the development of the Flex window (*Anderson and Dover 2003*), such as: (1) damping chamber; (2) air vents; and (3) membrane action. These concepts are covered in depth elsewhere (*Dover, Anderson, and Vickers 2002*), and will not be repeated herein. In addition, the "accordion" panel allows a significant amount of deformation without breaching the inner door seal. Figure 1b shows the door in open position, and also a close up of the door joinery, using a welded inside and outside steel channel.

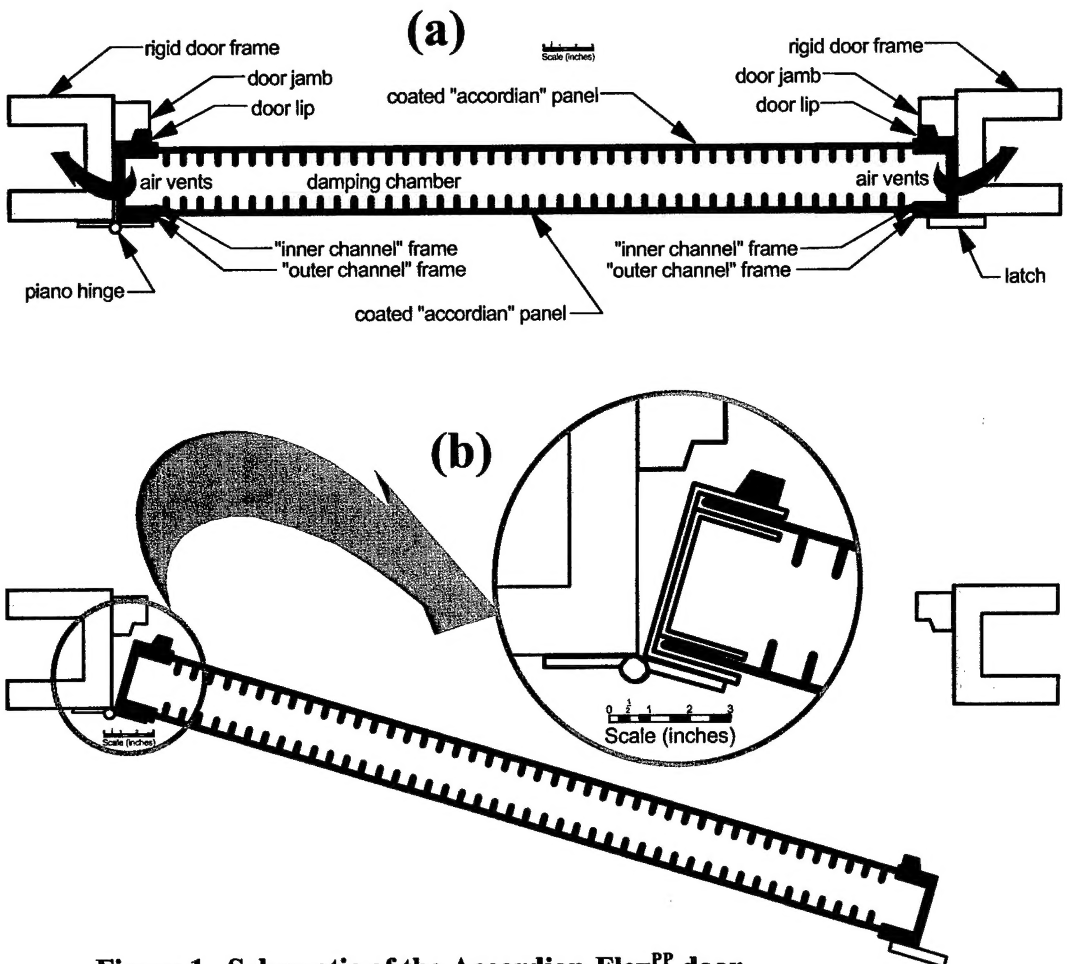


Figure 1. Schematic of the Accordion-Flex^{PP} door.

Figure 2 illustrates the way that the accordion-folds in the door dissipates energy by expansion. In Figure 2a, five of the accordion-folds are shown before and after expansion. The door can more than double in size via this expansion, from 48 inches to 114 inches. This is particularly important with regard to scaling. Because the accordion-folds have so much extra capacity, it is unlikely that they would even fail under the anticipated blast pressures. It is far more likely that other features in the structure would fail well before the Accordion-Flex^{PP} door.

One of the concerns is that as the door expands, it could (at least theoretically) reach it maximum expansion on one side well before it reaches maximum on the other side, as illustrated in Figure 2b. However, for two reasons, this effect was ignored and both sides (i.e., the accordion panels) of the door were made identical: (1) The maximum expansion allowable is large – the deformed shape shown in Figure 2b is approximately one-half of the total possible deformation (about 75 inches, out of a possible 114 inches); therefore, in order to reach full expansion, other issues (such as pull-out of the edges) will begin to control the deformation process. (2) In some cases, the negative phase of the blast wave can actually cause more apparent damage than the positive phase – in which case, the effect being considered would actually be exacerbated by increasing the size of the back panel relative to the front panel.

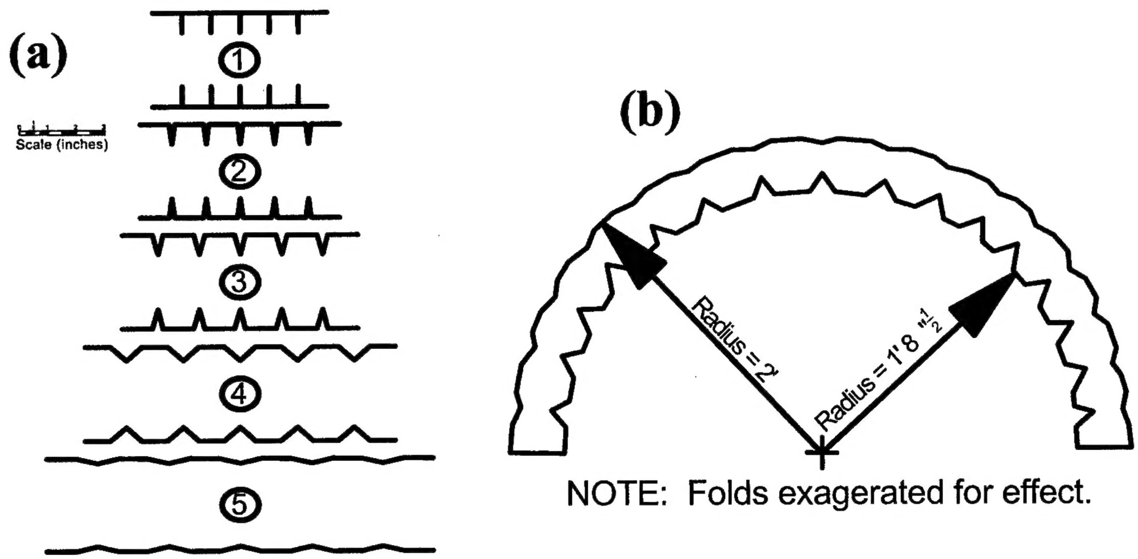
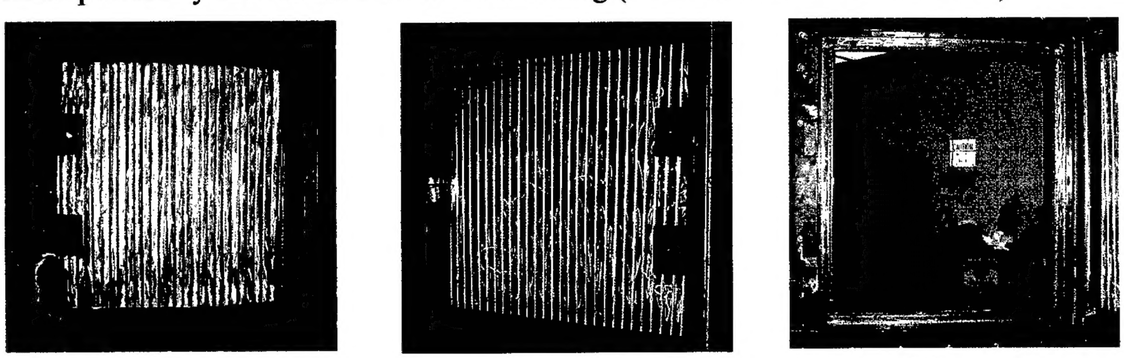


Figure 2. Illustration of fold expansion in the Accordion-Flex^PP door.

ACCORDION-FLEX^PP DOOR PROTOTYPE (UNFINISHED)

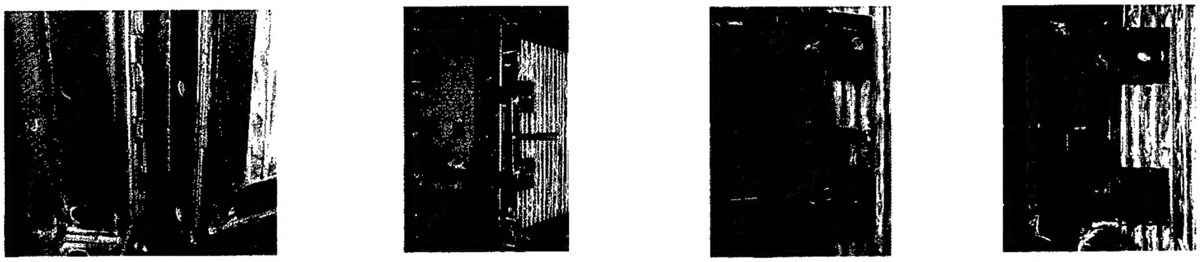
Figure 3 shows the unfinished Accordion-Flex^PP door, and Figure 4 shows close-ups of some specific hardware parts used in the prototype. The prototype door was 16 square feet in area, which is slightly less than a standard entry door (about 20 square feet), but this size allowed the rigid test structures previously used in the Flex window testing (see *Anderson and Dover 2003*) to be used



(a) Front **(b) Back** **(c) Frame**

Figure 3. Unfinished Accordion-Flex^PP door

again for the door tests. Some of the hardware parts, such as the door latch, are not intended to be hardware parts, such as the door latch, are not intended to be final configurations (e.g., a door without a means of opening from the inside would not be a popular retrofit item).

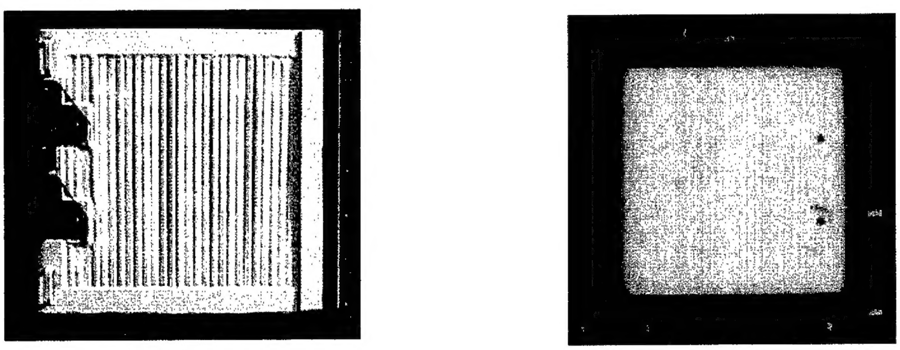


(a) Hinge **(b) Latch** **(c) Closed & Unlatched** **d) Latched**

Figure 4. Close-ups of hardware parts, unfinished Accordion-Flex^{PP} door

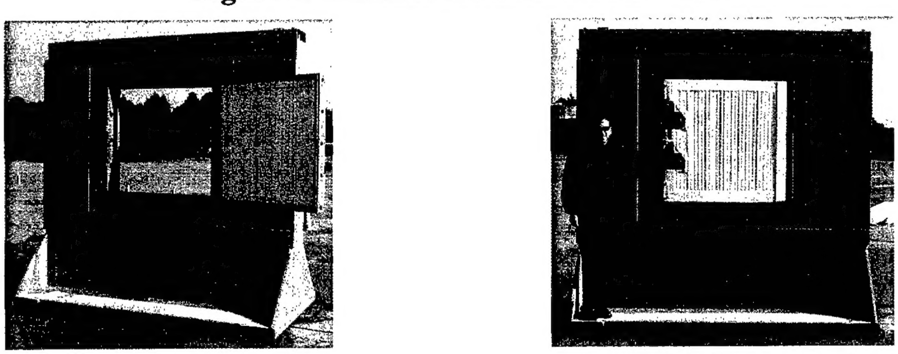
ACCORDION-FLEX^{PP} DOOR PROTOTYPE (FINISHED)

Figure 5 shows the finished Accordion-Flex^{PP} door (i.e., after applying ESC[1]). Figure 6 shows the finished door mounted in a rigid test structure.[2] Figure 7 shows instrumentation mounted on the door / rigid test structure.



(a) Front **(b) Back**

Figure 5. Finished Accordion-Flex^{PP} door



(a) Open **(b) Closed**

Figure 6. Accordion-Flex^{PP} door mounted in a rigid test structure

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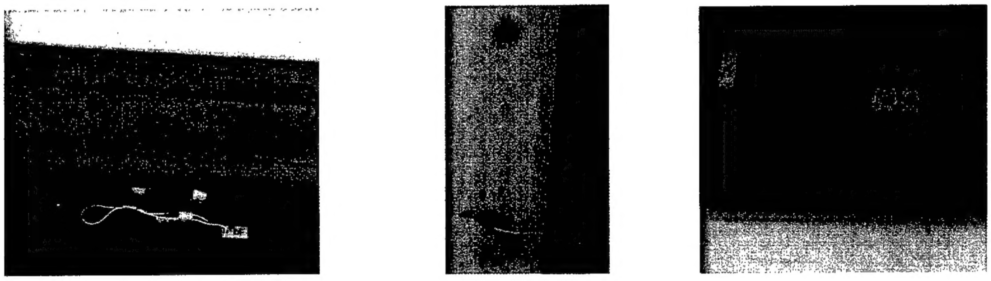
[1] See *Dover, Anderson, and Brown 2002*, for a more complete discussion of ESC, or elastomer sprayed coating (in that paper ESC is described for use in runway repair).

[2] See *Dover, Anderson, and Vickers 2002* for a thorough discussion on the rigid test structures and why they produce valid results.



(a) Front gauge (b) Inside gauge (c) Back gauge

Figure 7. Pressure gauge installation on Accordion-Flex^{PP} door

BLAST TESTING OF ACCORDION-FLEX^{PP} DOOR

The Accordion-Flex^{PP} door was tested under a nominal reflected pressure of 50 psi. Figures 8, 9, and 10 show P-I Curves[3] measured with high-speed pressure sensors mounted on the front, inside, and back, respectively, of the Accordion-Flex^{PP} door. Figure 11 is the same as Figure 8, but with some data superimposed (this data indicates the times where the accordion-expansion was maximum – as explained subsequently).

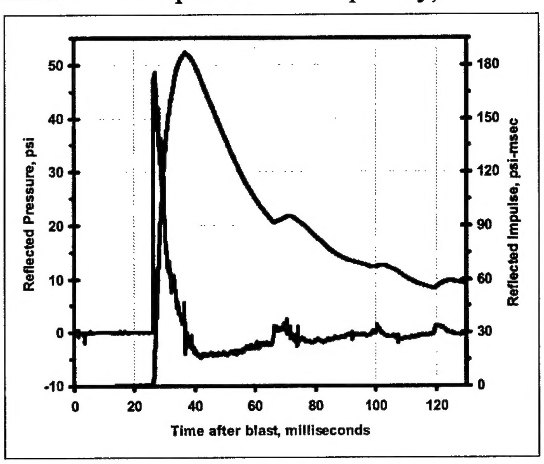


Figure 8. P-I Curves[3] – Front Gauge

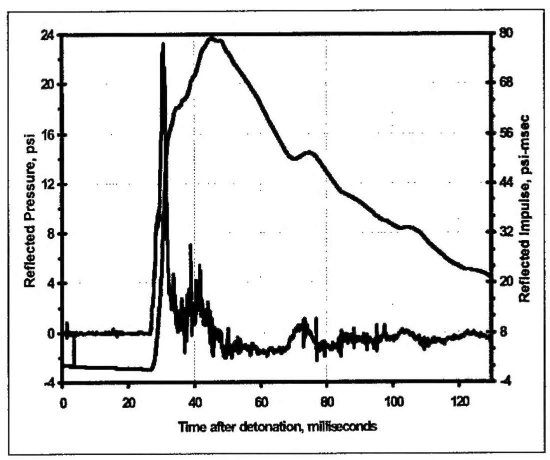


Figure 9. P-I Curves[3] – Inside gauge

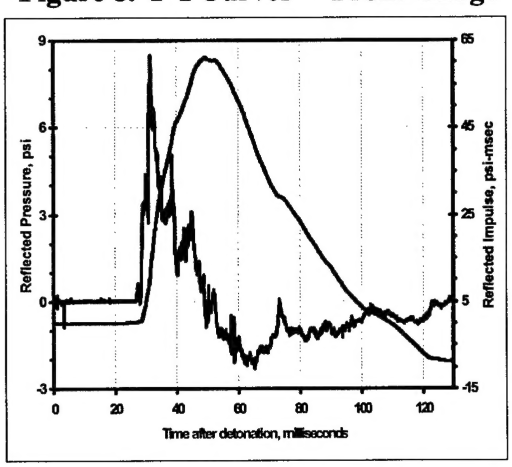


Figure 10. P-I Curves[3] – Back gauge

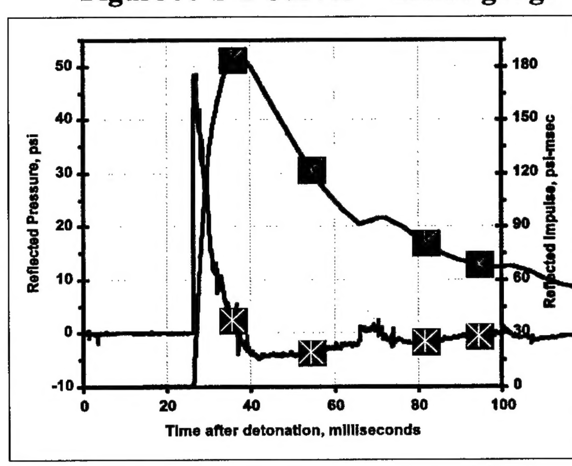


Figure 11. P-I Curves[3] & Peak Expansions

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[3] P-I Curves are combined plots of Pressure-Time history and Impulse-Time history.

Figure 12 shows a series of frames captured from high-speed video of the blast test of the Accordion-Flex^{PP} door (specifically, video of the back accordion-panel). The frames shown in Figure 12, and the subjective descriptions in the frame-by-frame analysis below, were chosen after a careful study of the actual video. However, the unretouched frames did not have enough contrast for print quality. Therefore, the brightness, contrast, and intensity of all the frames were altered to enhance the features being demonstrated. All of the frames were treated exactly the same way (brightness at 5%, intensity and contrast at 100%), so that visual comparisons based on the print frames would be valid. The frames highlight three openings in the back accordion-panel, and while they are not symmetrically located, for ease of identification they will herein be called "left opening," "center opening," and "right opening," for the left-most, center-most, and right-most openings, respectively. Examining the frames individually:

Frame 1 shows the Pre-Blast configuration (at 0.6 milliseconds before detonation), Frame 2 shows the instant of detonation, and Frame 3 shows the intensity of the blast (at 1.0 milliseconds after detonation).

Frame 4 occurred at 32.3 milliseconds after detonation, and is the first sign of expansion of the back accordion-panel.

Frames 5, 6, and 7 show the peak expansion of the left, right, and center openings, respectively, occurring at 34.0 milliseconds, 34.6 milliseconds, and 35.6 milliseconds, respectively. Frame 8 occurred at 43.6 milliseconds after detonation, and shows all three openings closed, indicating an elastic rebound of the panel.

Frames 9 to 11, occurring at 45.3 milliseconds, 54.3 milliseconds, and 58.0 milliseconds, respectively, are similar to Frames 5 to 8, except that: (1) only the left and center openings are visible, and (2) the maximum expansion of the left and center openings are less than the previous maximums (i.e., the oscillation is mostly elastic and decaying).

Frames 12 to 14, occurring at 74.6 milliseconds, 81.6 milliseconds, and 87.3 milliseconds, respectively, are similar to Frames 9 to 11, except that the maximum expansion is even less than Frames 9 to 11 (which, in turn, were less than Frames 5 to 8).

Frames 15 and 16, occurring at 94.6 milliseconds and 100.0 milliseconds, respectively, follow the pattern of the previous frames, except that: (1) only the center opening is visible, and (2) the maximum expansion is even smaller.

Despite the subjectivity, it is clear from Figure 12 that the door accordion-panels act as membranes, and that the expansion of the accordion-panels helps to dissipate the blast pressure. Also, there is clearly a decaying oscillation of the mostly elastic membrane. The data previously shown in Figure 11 corresponds to the local maxima of the expansion of the center opening (i.e., Frames 7, 10, 13, and 15). Two clear conclusions can be drawn from Figure 11: (1) the overall maximum opening occurs at the peak of the impulse curve, and after the blast wave (an expected result); and (2) the time between peaks is decreasing, which would be expected for a constant frequency decay with a decaying amplitude of oscillation (however, further discussion regarding the natural frequency of the panels is beyond the scope of this paper).

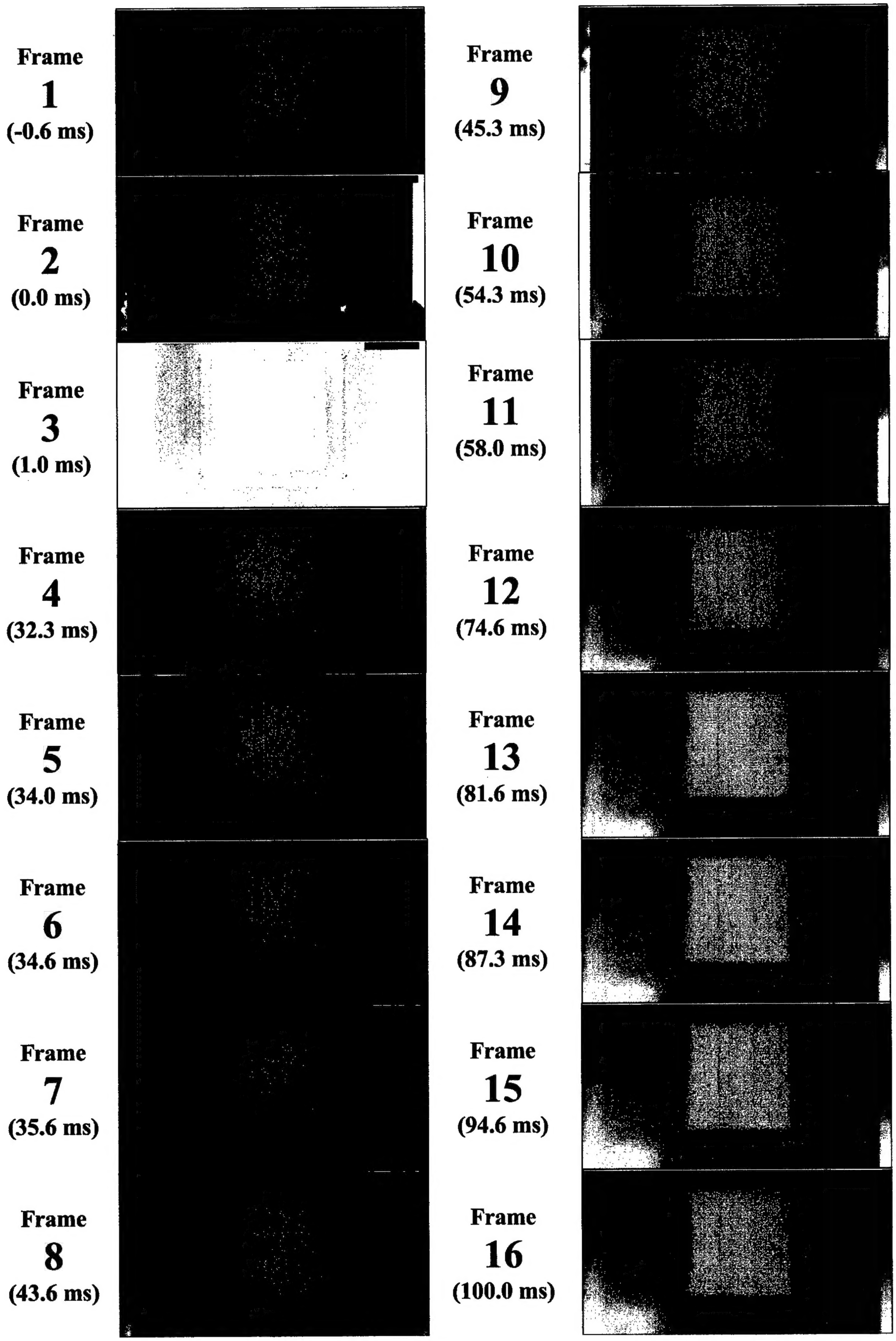
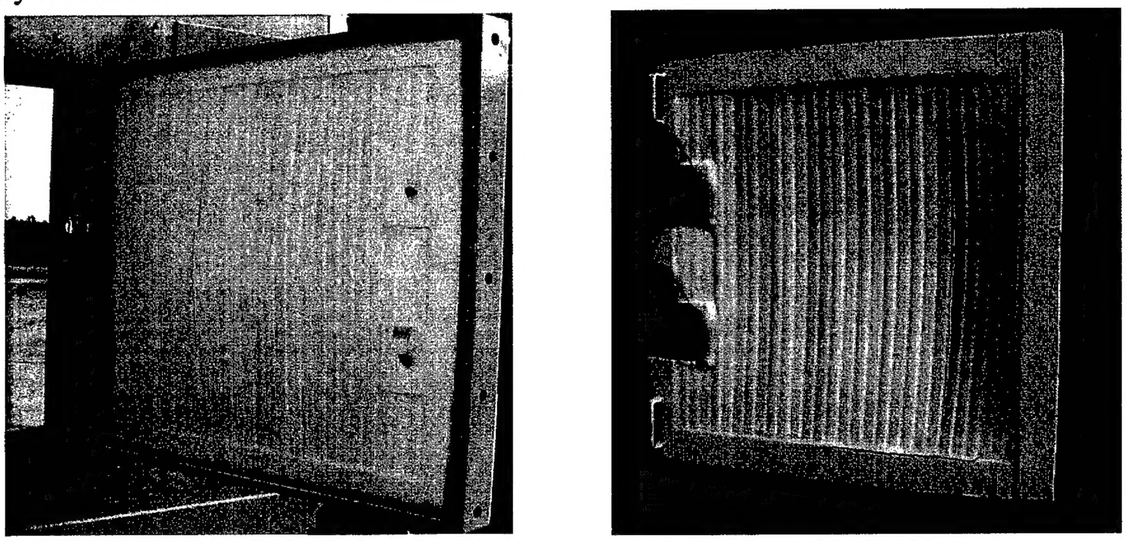


Figure 9. Frame captures from high-speed video taken during blast loading

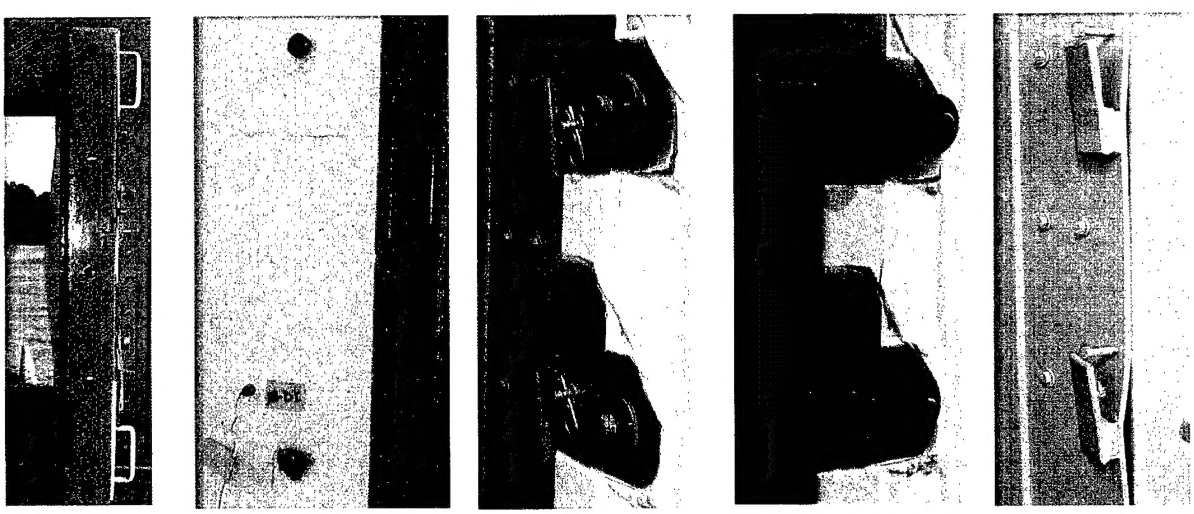
Figure 10 shows the door after the blast test. The back side, shown in Figure 10a, shows that the left and right openings (previously discussed) cannot be seen, and the center opening is seen only as a "hairline." On the front panel (Figure 10b), however, the corresponding expansion is more clearly delineated.



(a) Back **(b) Front**

Figure 10. The Accordion-Flex^{PP} door after blast test

Figure 11 shows the door hardware after the blast. As previously discussed, the hardware used in the prototype was not intended to be a final design. Still, the results are useful in considering final designs. Figure 11a shows the door side, which was virtually undamaged. Also in Figure 11a, the permanent deformation in the back panel can be seen, which is relatively small. Figure 11b shows the door pins, which were sheared off by the deformation of the back panel. Although the damage to the latch is not severe, it is significant, and the shearing of the door pins may have contributed to the stress on the latching hardware. Figures 11c and 11d show different views of the door latch with the door closed. Figure 11e shows the latch with the door open. As previously discussed, the damage to the latch is not severe.



(a) Side **(b) Door pins** **(c) Latch closed** **(d) Latch closed** **(e) Latch open**

Figure 11. Accordion-Flex^{PP} door hardware after blast test

CONCLUSIONS

1. The Accordion-Flex^{PP} door solves the three basic design challenges:

    a. It is lightweight, weighing about the same as a standard steel door, and has thickness similar to a standard steel door. This is a particularly important result for future retrofit use of the door.

    b. The door is capable of withstanding a high blast pressure, as demonstrated by the very minor damage sustained when tested with a blast wave with nominal peak reflected pressure of 50 psi.

    c. The frame is capable of holding the blast resistant door. Although some of the mounting hardware was damaged (as previously shown), there was absolutely no visible damage to the door frame.

2. The accordion-panels worked exactly as expected, with a mostly elastic decaying membrane-type oscillation, indicating that the membrane and damping chamber concepts taken from previous AFRL work on blast-resistant windows was, in fact, applicable to lightweight, blast-resistant doors.

3. The door frame concept is easily adaptable for retrofit application.

4. The door mounting hardware, although adequate for blast testing, must be redesigned into a more traditional configuration prior to fielding the door, and must be engineered to resist the negative phase of the blast pressure.

5. The door is scalable. As discussed previously, the expansion panels can more than double the size of the door, meaning that an incredible amount of energy can be absorbed. Based on the initial test, the Accordion-Flex^{PP} door, even when scaled to a more traditional size, should have far more blast-resistance than required.

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